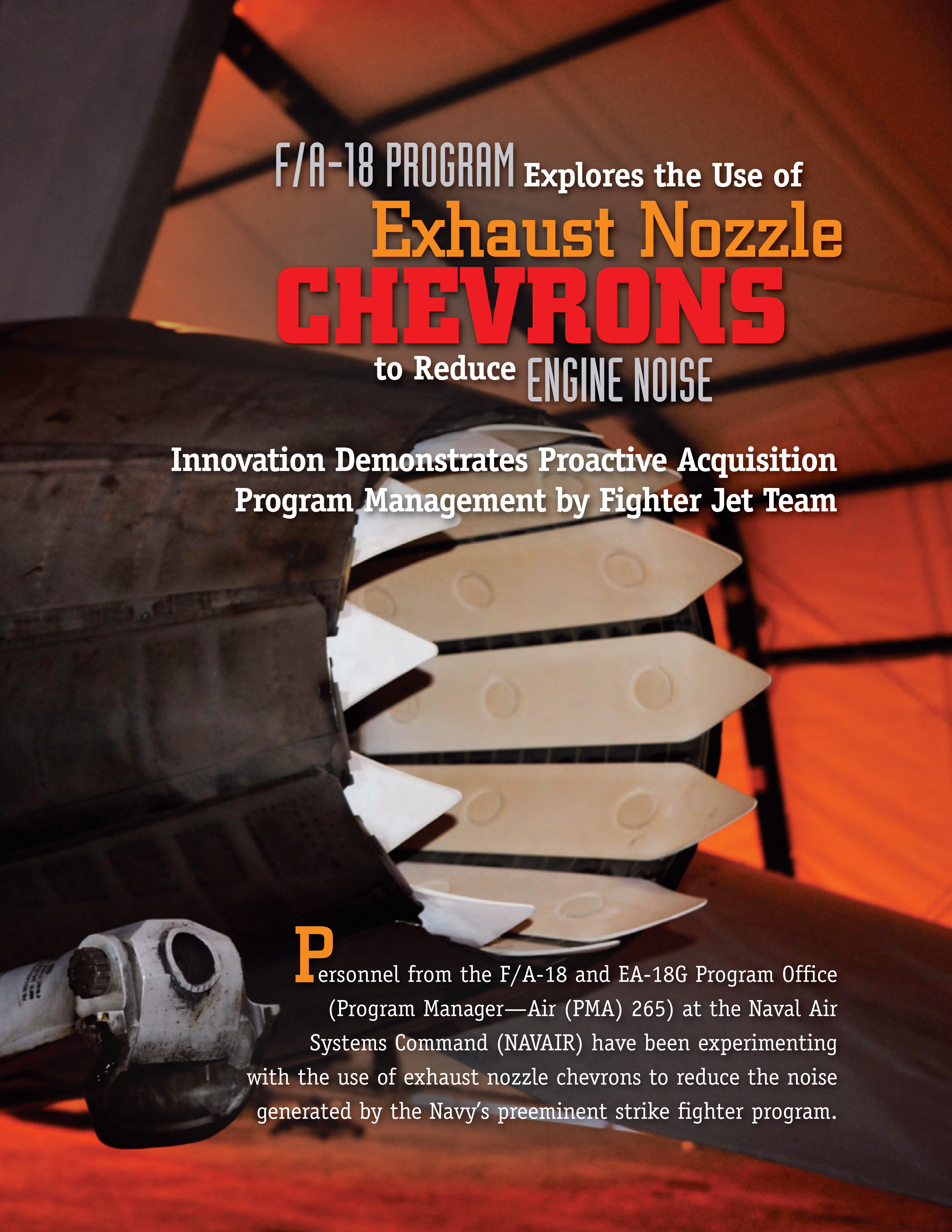


F/A-18 PROGRAM Explores the Use of Exhaust Nozzle CHEVRONS to Reduce ENGINE NOISE

Innovation Demonstrates Proactive Acquisition Program Management by Fighter Jet Team

Personnel from the F/A-18 and EA-18G Program Office (Program Manager—Air (PMA) 265) at the Naval Air Systems Command (NAVAIR) have been experimenting with the use of exhaust nozzle chevrons to reduce the noise generated by the Navy's preeminent strike fighter program.

Until very recently, the Navy's response to jet noise was focused exclusively on hearing protection.

BACKGROUND

For many years, tactical jet aircraft and jet engine designers have responded exclusively to the requirement for better performance and increased range by seeking greater jet engine thrust and lower aircraft weight. All acquisition programs establish performance goals and track the success of their systems design and modifications to that design against those goals. Greater thrust (a common goal for high performance tactical aircraft jet engines) means increased exhaust velocity and higher temperatures, resulting in elevated jet noise. (For more insights, see our sidebar "The Navy Safety Center's Perspective on Noise & Its Impacts.") The Navy's solution (and that of other Services) to excessive noise has been to provide hearing protection (Flight Deck Cranials) for support personnel. Over the past years, the Navy has developed an Advanced Noise Reduction (ANR) system that promises the wearer up to 47 decibel (dB) protection.

Commercial jetliners with large high by-pass fan jet engines have achieved very significant jet noise reduction over the years. Unfortunately the thrust, weight, and size requirements peculiar to naval carrier aircraft preclude the use of this technology. Until very recently, the Navy's response to jet noise was focused exclusively on hearing protection. However, even the best ANR systems available do not provide adequate hearing protection. This gap in noise exposure must first be addressed at the source—the jet engine nozzle.

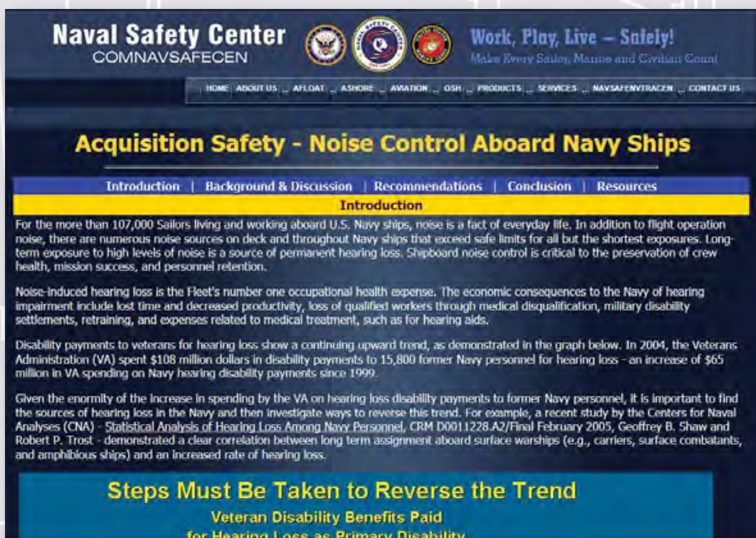
The Navy Safety Center's PERSPECTIVE ON NOISE & ITS IMPACTS

According to the Navy Safety Center's web site, noise is a fact of everyday life for the more than 107,000 Sailors living and working aboard U.S. Navy ships. In addition to flight operation noise, there are numerous noise sources on deck and throughout Navy ships that exceed safe limits for all but the shortest exposures. Long-term exposure to high levels of noise is a source of permanent hearing loss. Shipboard noise control is critical to the preservation of crew health, mission success, and personnel retention.

Noise-induced hearing loss is the Fleet's number one occupational health expense. The economic consequences to the Navy of hearing impairment include lost time and decreased productivity, loss of qualified workers through medical disqualification, military disability settlements, retraining, and expenses related to medical treatment, such as for hearing aids.

Disability payments to veterans for hearing loss show a continuing upward trend. Given the enormity of the increase in spending on hearing loss disability payments to former Navy personnel, it is important to find the sources of hearing loss in the Navy and then investigate ways to reverse this trend.

For more insights into the Navy Safety Center's efforts to control noise aboard Navy ships including a complete discussion of the problem of noise, its impact on the Navy's personnel and the need for action, visit www.public.navy.mil/comnavsafecen/pages/acquisition/noise_control.aspx.



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Acquisition Safety - Noise Control Aboard Navy Ships

Introduction | Background & Discussion | Recommendations | Conclusion | Resources

Introduction

For the more than 107,000 Sailors living and working aboard U.S. Navy ships, noise is a fact of everyday life. In addition to flight operation noise, there are numerous noise sources on deck and throughout Navy ships that exceed safe limits for all but the shortest exposures. Long-term exposure to high levels of noise is a source of permanent hearing loss. Shipboard noise control is critical to the preservation of crew health, mission success, and personnel retention.

Noise-induced hearing loss is the Fleet's number one occupational health expense. The economic consequences to the Navy of hearing impairment include lost time and decreased productivity, loss of qualified workers through medical disqualification, military disability settlements, retraining, and expenses related to medical treatment, such as for hearing aids.

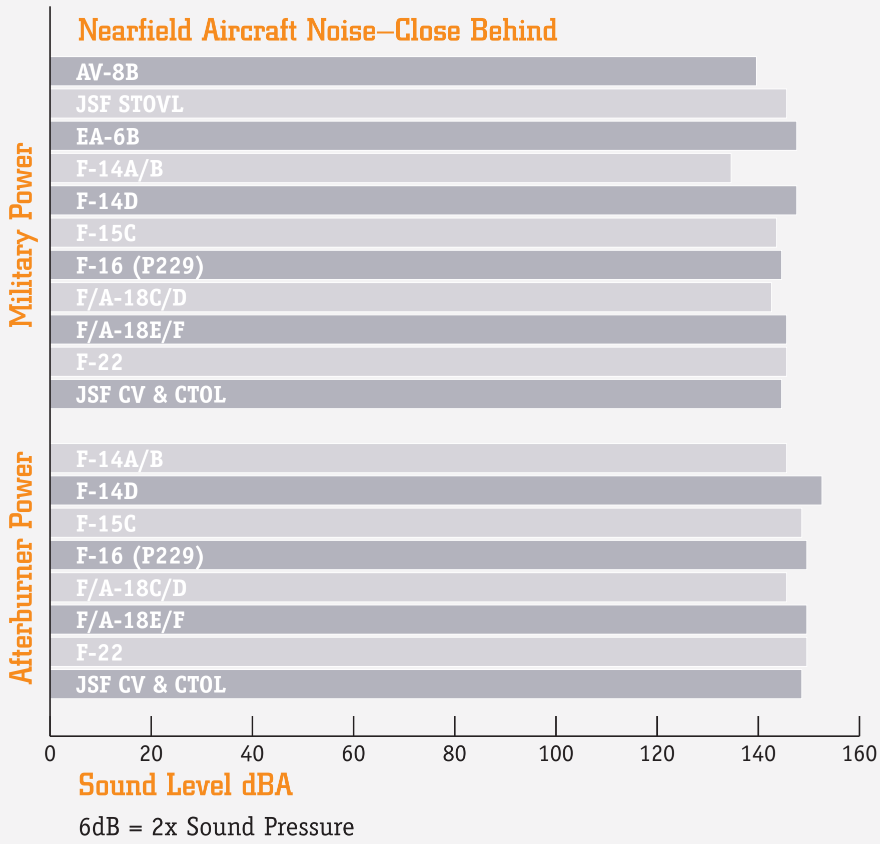
Disability payments to veterans for hearing loss show a continuing upward trend, as demonstrated in the graph below. In 2004, the Veterans Administration (VA) spent $108 million dollars in disability payments to 15,800 former Navy personnel for hearing loss - an increase of $65 million in VA spending on Navy hearing disability payments since 1999.

Given the enormity of the increase in spending by the VA on hearing loss disability payments to former Navy personnel, it is important to find the sources of hearing loss in the Navy and then investigate ways to reverse this trend. For example, a recent study by the Centers for Naval Analyses (CNA) - Statistical Analysis of Hearing Loss Among Navy Personnel, CRM D0011228.A2/Final February 2005, Geoffrey B. Shaw and Robert P. Trost - demonstrated a clear correlation between long term assignment aboard surface warships (e.g., carriers, surface combatants, and amphibious ships) and an increased rate of hearing loss.

Steps Must Be Taken to Reverse the Trend

Veteran Disability Benefits Paid
for Hearing Loss as Primary Disability

THE PROBLEM



The Department of Defense and the Navy has for years recognized that hazards and risk associated with the operation of military platforms must be identified and mitigation measures put in place. The Defense Acquisition System Safety—Environment, Safety, and Occupational Health (ESOH) Risk Acceptance Memorandum (signed by Kenneth J. Krieg, Under Secretary of Defense for Acquisition, Technology and Logistics and dated 7 March 2007) states "I direct that addressees ensure that—prior to exposing people, equipment, or the environment to known system-related ESOH hazards—the associated risk levels, as defined in MIL-STD-882D, must be accepted by the authorities identified in DoDI 5000.2. The user representative must be part of this process throughout the lifecycle and must provide formal concurrence prior to all Serious- and High-risk acceptance decisions."

Flight deck personnel are exposed to heavy acoustic loads.

The chevron static test conducted in 2007 demonstrated significant noise reduction without measured loss of thrust.

Jet noise can pose a serious risk. Pursuant to this memo, Program Executive Officer for Tactical Air (PEO(T)) formally acknowledged this and obtained concurrence from the Commander, Naval Air Forces (CNAF). Moreover, PEO(T) directed PMA265 to assess annually "…the viability of incorporating proven technologies into the F/A-18E/F and EA-18G." In response to this direction, PMA265 embarked on a robust research and development program.

THE SEARCH FOR A SOLUTION

PMA265 researched a number of technologies to reduce jet engine noise including corrugated seals, water injection, fluidic chevrons (air injection) and the application of plasma actuators to jet exhaust. Initially, each of these technologies showed promise but ultimately were not selected.

Corrugated Seals

The initial configuration of corrugated Variable Exhaust Nozzle (VEN) seals did reduce jet noise in the near field on takeoff but had an impact on thrust when the aircraft was at altitude/cruise. This impacts aircraft range and speed—an unacceptable drawback for the Fleet and warfighter. PMA265 directed additional aeroacoustic research performed by the National Center for Physical Acoustics at the University of Mississippi which confirmed this analysis.

Water Injection

Water injection into the exhaust plume also reduces jet noise. However, there are many drawbacks. A massive brine plume when used on aircraft carriers leading to significant corrosion issues and carriage of a 4,000-pound water tank would greatly diminish aircraft range, performance, fuel and ordnance capability.

Fluidic Chevrons

Fluidic chevrons (injecting high pressure air jets into the exhaust plume) would seem to offer a "switchable solution"—use on takeoff and turn off at altitude/cruise. However during Office of Naval Research (ONR) tests, the

QUOTABLE QUOTES & SUPPORTING MEMORANDA

1. United States Fleet Forces Command
"This specific Rapid Technology Transition (RTT) F/A-18 Jet Noise Reduction Initiative is not only prudent, it is necessary for future Fleet readiness."

2. Naval Safety Center
"The Commander, Naval Safety Center enthusiastically supports efforts by the acquisition community to develop weapons systems with reduced noise signatures and this specific RTT F/A-18 jet noise reduction initiative."

3. Assistant Secretary of the Navy, Installations and Environment
"Succeeding generations of aircraft with their higher noise levels have only made this problem worse. Engineering solutions that reduce aircraft noise are key to resolving this problem."

4. Commander, Naval Air Forces
"The Commander, Naval Air Forces supports…this specific F/A-18 jet noise reduction initiative."


Chevrons installed on the F/A-18E/F aircraft in preparation for a static noise test.

compressed air demands far exceeded the available jet engine-produced bleed air available.

Plasma Actuators

Plasma actuators use a strong electrical field to generate plasma. This has the effect of reducing the turbulence and vortices in the exhaust plume thus reducing dB levels. However, electric power required is far above that available on board tactical aircraft.

Of the technologies and solutions tested, PMA265 determined that installing a uniquely shaped extension of the jet engine nozzles that may provide an optimal configuration for noise reduction.

THE PROPOSED TECHNOLOGY: Chevrons Extend the Variable Exhaust Nozzle Seals

The chevron is a specially designed shape that is installed at the trailing edge of the exhaust nozzle. The chevron promotes more rapid mixing in the shear layer between the jet plume and the ambient air through the generation of vortices that roll up along the angled side of the chevron. This enhanced mixing of the jet plume helps to reduce the peak jet velocity more efficiently. The peak jet velocity is the prime factor in noise generation—reduction in peak jet velocity equates to reduced noise production. This increased mixing and reduction of peak velocity also reduces the extent and strength of the shock cells in the jet plume, which are known to generate noise through their interaction with the turbulent airflow.

CHEVRONS: The Best Solution to the Problem

The chevron static test conducted by ONR and General Electric (GE) Aviation at the Naval Air Warfare Center Aircraft Division (NAWCAD) in Lakehurst, New Jersey in September 2007 demonstrated significant noise reduction without measured loss of thrust. The reduction of exhaust noise on this first generation jet is an initial

continued on page 14

MC2 Laurie Dexter

MC2 Andrea Perez

MC1 Michael Lindsey

MC2 Andrea Perez

MC1 Michael Lindsey

The Navy's Blue Angels flight demonstration squadron flies F/A-18 aircraft. The exhaust nozzle chevrons discussed in this article are applicable to this entire class of aircraft.

MC2 Andrea Perez

MC2 Kathryn E. Macdonald

MC2 Andrea Perez

continued from page 11

step in integrating this commercial technology on military jet engines. The reduction of sound pressure levels by 3 dB A-weighted (dBA) over much of the frequency range is very significant as it represents a 50 percent reduction in sound pressure levels. This would be like doubling the distance from a noise source. Moreover, as generated in a subsequent test, in the 3 kilo hertz (kHZ) to 6 kHZ frequency, considered to be the most likely to cause noise induced hearing loss (NIHL), noise reduction of up to 7 dB is possible. As discussed, other technologies such as corrugated seals, water injection, fluidic chevrons (air injection) and application of plasma actuators to jet exhaust are not as mature or as easy to implement as chevrons; hence the decision to focus on chevrons. Additionally, this design will serve as a foundation for further noise reduction because it is compatible with other noise abatement technologies. This is a first step in an overall effort to reduce engine sound pressure level (SPL).

TEST PROGRAM:
Demonstration & Validation

All changes in configuration of the F/A-18 aircraft can be made only after rigorous test and evaluation. The following major "pass/fail" criteria for chevron technology were applied to the F414 engine:

KEY PLAYERS

1. Program Office
The F/A-18 and EA-18G Program Office is responsible for acquiring, delivering and sustaining the F/A-18 C/D Hornet, F/A-18 E/F Super Hornet, and EA-18G Growler aircraft, providing naval aviators with capabilities that enable mission success. Serving seven international customers, the program office emphasizes cooperative development and partnerships for foreign military sales to Australia, Canada, Finland, Kuwait, Malaysia, Spain and Switzerland.

2. Contractor Support
The F/A-18 and EA-18G Program Office has relied on the original equipment manufacturer, GE Aviation to develop the initial sets of test article chevron VEN seals as they have the most complete understanding of the required design/configuration of the F414 jet nozzle. To reduce the impact of the jet noise produced by F/A-18 aircraft on communities surrounding Naval Air Stations, the Program Office sponsored a Small Business Innovative Research contract awarded to Blue Ridge Research and Consulting. The goal of this contract was to develop a software program that would optimize the flight profiles minimizing noise impact. The final product called "The Optimizer" is available to the Naval Facilities Engineering Command for use at their activities. Although the configuration selected for development is chevrons, there are other designs that are potentially effective in reducing jet noise. The Program Office contracted with the University of Mississippi's National Center for Physical Acoustics to explore these options and provide recommendations for additional research.

The Basics About

THE F/A-18 HORNET JET FIGHTER

The F/A-18 Hornet was developed in the early 1980's as an all-weather aircraft and is used as an attack aircraft as well as a fighter. In its fighter mode, the F/A-18 is used primarily as a fighter escort and for Fleet air defense. In its attack mode, it is used for force projection, interdiction and close and deep air support. The Hornet saw its first combat action in 1986 during Operation El Dorado Canyon and subsequently participated in 1991 Operation Desert Storm and 2003 Operation Iraqi Freedom. The F/A-18 Hornet provided the baseline design for the Boeing F/A-18E/F Super Hornet—a larger, evolutionary redesign of the F/A-18. The F/A-18 Hornet family of aircraft including the Hornet, Super Hornet, and EA-18G Growler has flown over nine million flight hours and continues to prove its value and reliability to the fleet and will continue to serve the nation for years to come.

- Super Hornet: The F/A-18 E/F Super Hornet is a combat-proven platform with demonstrated capabilities in multiple warfighting roles. The Block II aircraft provides enhanced capabilities over its predecessors.
- EA-18G Growler: The Navy's EA-18G Growler is designed to be a mission-changing electronic attack aircraft that combines the demonstrated capability of the Super Hornet's suppression of enemy air defenses with superior jamming abilities in the reactive, pre-emptive, standoff, and escort roles. The EA-18G Growler is a variant of the combat-proven F/A-18F Super Hornet Block II, and will fly the airborne electronic attack mission. The EA-18G combines the capability of the combat-proven Super Hornet with the latest avionics suite evolved from the Improved Capability III system. The EA-18G's vast array of sensors and weapons provides the warfighter with a lethal and survivable weapon system to counter current and emerging threats.
- F/A-18 Hornets, Super Hornets and EA-18G Growlers currently operate in 43 U.S. Navy and 11 U.S. Marine Corps Strike Fighter and Electronic Attack Squadrons from carriers and air stations worldwide. There are an additional 14 squadrons carrying out training, test, reserve and flight demonstration duties.

Contractor	• Boeing (McDonnell Douglas Aerospace)	• Northrop Grumman (Airframe)	• General Electric (Engines)	• Raytheon (Radar)

	F/A-18C/D Hornet	F/A-18E/F Super Hornet
Power Plant	• Two F404-GE-402 afterburning engines, each in the 18,000 pound thrust class, which results in a combat thrust-to-weight ratio greater than 1-to-1. Depending on the mission and loading, combat radius is greater than 500 nautical miles.	• Twin F414-GE-400 engines, each in the 22,000 pound thrust class. On an interdiction mission, the E/F will fly up to 40 percent further than the C/D.
Accommodations	• The F/A-18C and F/A-18E are single seat aircraft. • The D and F models are flown by two crew members. • The aft seat in the D and F may be configured with a stick and throttle for the training environment (or without when crewed with a Weapons System Officer).	
Performance	• F/A-18C maximum speed at level flight in altitudes of 36,089 feet: Mach 1.7	• F/A-18E maximum speed at level flight in altitudes of 36,089 feet: Mach 1.6
Armament	• F/A-18C/D can carry up to 13,700 pounds of external ordnance. • Weapon stations include two wingtip stations for Sidewinders; two outboard wing stations for air-to-air or air-to-ground weapons; two inboard wing stations for fuel tanks, air-to-air, or air-to-ground weapons; two nacelle fuselage stations for the AIM-120 advanced medium-range air-to-air missile, AIM-7 Sparrow, or sensor pods; and one centerline station for fuel or air-to-ground weapons.	• F/A-18E/F can carry up to 17,750 pounds of external ordnance. • Two additional wing store stations have been added.
Mission & Capabilities	• The F/A-18C/D Hornet can perform both air-to-air and air-to-ground missions. • Cockpit displays and mission avionics are thoroughly integrated to enhance crew situational awareness and mission capability in high threat, and adverse weather/night environments. • Cockpits are night vision goggle compatible. • Multi-Sensor Integration and advanced data link capabilities further enhance situational awareness.	• The F/A-18E/F Super Hornet is able to perform a strike tanker mission while carrying a self-protection air-to-air missile loadout. • The E/F model also has greater payload flexibility, increased mission radius, survivability, payload bring back, and a substantial avionics growth potential.

A Fleet introduction strategy of retrofit by attrition will be implemented with chevrons being a preferred spare.

1. Reduction in near field SPLs by a minimum of 2.5 dBA with a goal of 3 dBA in the audible spectrum.
2. Without impact to thrust in all flight regimes.
3. Cost of manufacture of the new configuration (VEN seals with chevrons) will not substantially exceed the current program of record cost for the existing VEN seals.

PMA265 has conducted a series of tests over the course of seven years to determine the suitability of chevrons:

2009

F404 engine test at NAWCAD Lakehurst produced the results shown in the figure above. This test used ceramic/metallic prototype test article VEN seals which were structurally rigid, allowing moderate impingement into the exhaust plume.

2012

Follow-on static test of the chevrons installed on an F/A18E aircraft/F414 engine tied down at the catapult facility at NAWCAD Patuxent River, Maryland. Because of adverse weather conditions, the results from this test were inconclusive. Moreover, the prototype VEN seals developed for this test were fabricated using ceramic matrix composites. This material

TOP: Dr. Steven Martens, GE Aircraft Engines (left), Dr. John Spyropoulos and Alan Pentz, NAVAIR Propulsion and Power, were part of the December 2012 engine test team at NAWCAD Patuxent River, MD.

RIGHT: Mike Rudy, former ESOH Coordinator for the F/A-18 Program Office (now with Wyle Laboratories, Inc.), stands in front of a Super Hornet during the December 2012 test of the experimental exhaust nozzle chevrons conducted at NAWCAD Patuxent River, MD.

AWARDS THROUGH THE YEARS

The F/A-18 Program Office has been recognized for consistent dedication to the Department of the Navy's ESOH goals and honored with the following awards:

- Chief of Naval Operations Environmental Excellence in Weapon System Acquisition, Large Program awards in 2001, 2003, 2005, 2007, 2009, 2011, and 2013. These awards are awarded for large acquisition programs every two years; hence this represents outstanding, consecutive achievement.
- Secretary of the Navy (SECNAV) Environmental Excellence in Weapon System Acquisition, Large Program, and Team Award in 2003, 2011, and 2013. The SECNAV award is the highest award for environmental excellence made by the Department of the Navy.

(termed Ox-Ox by GE Aircraft Engines) is the same as that used in the manufacture of original and replacement F414 VEN seals. Characteristics include resistance to high temperatures, thermal shock conditions, heavy vibration loads, flexibility and resistance to cracking.

2014

The most recent test was conducted at NAWCAD Lakehurst in October 2014. Again, this was a static test of chevrons F/A-18E installed aircraft engine tied down and the VEN seals with chevrons used were the Ox-Ox manufactured prototype. Preliminary tests results indicate no jet noise reduction during afterburner operations—marginal improvement at military power. The data collected are still under analysis. However, there appears to be evidence that the flexible characteristics of the Ox-Ox material is allowing the VEN seals to bend away from the exhaust plume negating more rapid mixing in the shear layer between the jet plume and the ambient air and jet noise reduction.

Medium term noise reduction (5 dBA reduction near-field) may build upon this chevron technology but will require more extensive modification/ redesign of the existing F414 exhaust system and selection of a less flexible material for use in modified VEN seals. The F/A-18 Program Office will continue to work with its industry partner (GE Aviation) to determine the technical and financial feasibility of this technology. Long term reductions (10 dBA near-field) may be considered by the Naval Aviation Enterprise as an ultimate goal for future naval aircraft.

FLEET INTRODUCTION

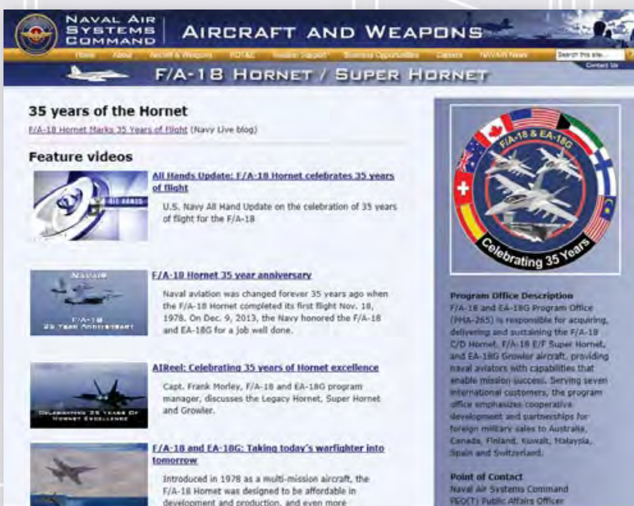
To date, the F/A-18 and EA-18G Program Office has expended over $5.6 million on its jet noise reduction program. PMA265's original plan was for a replacement of all current VEN seals with the new chevron configured seals. This is termed a "forced retrofit" in the Navy logistics world

and would cost in excess of $100 million. However, current budgetary constraints preclude such an aggressive approach. Moreover, VEN seals are expendable—they wear out after 400 to 500 hours of engine time and have to be replaced. Therefore a Fleet introduction strategy of retrofit by attrition will be implemented with chevrons being a preferred spare. When an existing standard configuration seal requires replacement, the chevron configured VEN seal would be installed. This may provide approximately a 50 percent reduction in current engine exhaust noise levels of the F/A-18E/F F414 engine without additive cost as the chevron seals can be produced for the same manufacturing cost as the original seals.

There are details to be worked out however. Are there any performance/structural issues caused by an asymmetric configuration (i.e., alternating standard configurations seals with chevron configured seals or chevrons on one engine and none

FOR MORE INFORMATION

- **F/A-18 Hornet/Super Hornet web site**
  www.navair.navy.mil/index.cfm?fuseaction=home.display&key=3ABFFE4F-7D6E-40D0-A0E3-AED4FCB1C408
- **EA-18G Growler web site**
  www.navair.navy.mil/index.cfm?fuseaction=home.display&key=33BFA969-0482-42CF-9E1F-F80A1B32BEE9
- **NAVAIR Facebook page**
  www.facebook.com/NAVAIR
- **NAVAIR Twitter page**
  www.twitter.com/navairnews
- **NAVAIR YouTube Site**
  www.youtube.com/user/NAVAIRSYSCOM



F/A-18C Hornets launch simultaneously from the flight deck aboard the Nimitz-class aircraft carrier USS Harry S. Truman (CVN 75).
Photographer's Mate Airman Ryan O'Connor

on the other)? More testing will be required to provide answers to this question. Will the Fleet, wing and squadron commanders accept a non-uniform nozzle appearance on their aircraft? Preliminary discussions with CNAF staff have indicated their willingness to make this happen. Safety of their personnel is paramount to all commanders.

The user community (the Fleet, CNAF), Commander Naval Air Systems Command, and PEO(T) all strongly support this initiative and the F/A-18E/F and EA-18G Program Office is committed to its introduction into the Fleet. Should the results of the final installed static test meet the pass/fail criteria outlined above, this may offer a viable solution and a mandatory risk reduction effort in view of the documented incidence of jet noise induced hearing loss incurred by Navy and Marine Corp personnel. This technology may reduce sound pressure levels to half of the current value, and will demonstrate the Navy's commitment in addressing one significant source of hearing loss. The impact of this technology is reduction in numbers of Naval personnel diagnosed with long term hearing loss, improvement of working conditions in high noise environments (e.g., U.S. Navy aircraft carriers) and decreased Department of the Navy liability to inverse condemnation litigation caused by jet noise. No other current research and development program addresses jet noise at its source—the engine nozzle and exhaust plume.

CONCLUSION

Although the research, development and delivery of this technology to the user, the Fleet, is incomplete, the narrative of the F/A-18 Program Office is useful as an example of what a proactive, dedicated acquisition program can accomplish. ESOH goals may often take a back seat to higher priority military performance objectives. In this instance, a serious safety and occupational health problem (noise-induced hearing loss) was identified; a commitment was made to investigate solutions; an achievable design that showed promise was identified; and resources were committed to demonstrate and validate the proposed solution. This has required program leadership, dedication by a government/acquisition/industry team and hard work by systems engineering personnel to make it happen. ⚓

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